LIMNOLOGICAL OBSERVATIONS ON THE AURORA TROUT LAKES

1978

Ontario
Ministry of the Environment

The Honourable
Harry C. Parrott, D.D.S.,
Minister

K.H. Sharpe,
Deputy Minister

LIMNOLOGICAL OBSERVATIONS

on the

AURORA TROUT LAKES

WATER RESOURCES ASSESSMENT,

NORTHEASTERN REGION.

1978

Reg. Op.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

SUMMARY AND CONCLUSIONS

Excessive precipitation acidity coupled with inherently low acid buffering capacity (due to highly weathering resistant geological settings) has apparently resulted in the acidification of the study lakes. The degree of pH depression shows some variation between lakes, likely reflecting differences in lake morphometry, local lithology, and acidic loadings; however, with the exception of Smoothwater Lake (pH 5.8) all the study lakes exhibited mean pH (4.5 to 5.2) < 5.5, the value below which adverse effects on sensitive fish species may be expected. Correspondingly, accessory data on fisheries status indicate that indigenous fish populations have been eliminated from most of the study lakes, including the extinction of the aurora trout (a rare subspecies of brook trout) in its only known natural range (Whitepine, Whirligig and Wilderness lakes).

Acidification of the study lakes has also apparently exerted a significant effect on the composition of phytoplankton communities. Sampling of selected lakes indicated strong dominance by Dinophyceae, Chlorophyceae and Cryptophyceae, characteristic of acid-stressed lakes. No influence, by low pH, on phytoplankton biomass was evident. Phytoplankton biomass in the study lakes was comparable to biomass in non-acidified lakes of similar phosphorus concentrations.

INTRODUCTION

BACKGROUND

During the early summer of 1971, information was received from the Ontario Department of Lands and Forests (now Ministry of Natural Resources) by regional staff of the Ontario Water Resources Commission (now Ministry of the Environment) that fish populations in certain lakes of the Temagami Provincial Forest had declined dramatically in recent years. Some of these lakes represented a particularly important resource since they harboured the only known natural populations of aurora trout.

This little known char was first discovered in Whitepine Lake, Gamble Township, in 1923. Subsequently its occurrence was documented in nearby Wilderness and Whirligig lakes. Notes on the discovery and initial description of the aurora trout are provided in Henn and Rinkenbach (1925), and McKay, (1964). Since its discovery, the aurora trout has been the subject of considerable taxonomic dispute. Originally, it was classified as a distinct species, *Salvelinus timagamiensis* Henn and Rinkenbach (Henn and Rinkenbach, 1925); however, investigators since that time have favoured a closer kinship with the brook trout, *Salvelinus fontinalis.* Sale, (1967), in his treatment of the subject suggests a subspecific classification, *Salvelinus fontinalis* timagamiensis (Henn and Rinkenbach).

In response to the concern expressed over declining fish populations, particularly aurora trout, in lakes of the Temagami Provincial Forest, a cooperative sampling programme between the Ministry of the Environment (M.O.E.) and the Ministry of Natural Resources was initiated. During the summer of 1971, seven selected lakes, including Whitepine, a parent lake of the aurora trout, were investigated. The results of this preliminary evaluation (Conroy and Keller, 1972) showed low pH ($\approx$ 5.0) in those lakes exhibiting depressed fisheries, one of them Whitepine. The cause of the observed low pH and resultant loss of fisheries was tentatively attributed to atmospherically conveyed acidic inputs. Similar problems had been identified in lakes of the Sudbury area (OWRC, 1970; Beamish and Harvey, 1972).

During the summer of 1974, as part of the major Sudbury Environmental Study, the M.O.E. initiated an extensive sampling programme of lakes in the greater Sudbury area in an attempt to document and evaluate the lake acidification problem in Northeastern Ontario. Data from that study (see Conroy et al, 1978) showed the existence of a large zone of lakes with depressed pH (< 5.5) extending northeast and southwest of the Sudbury smelting centre. The home range of the aurora trout was observed to fall within this zone (Figure 1).

During the summer of 1976, a more intensive limnological study of the aurora trout lakes, and neighbouring lakes, was carried out by M.O.E. with the objective of investigating the acidification phenomenon in these waters and documenting

the associated aquatic biological responses. The following text outlines the results of the 1976 study and provides comparison, where possible, with historical water quality in the study lakes.

DESCRIPTION OF THE STUDY AREA

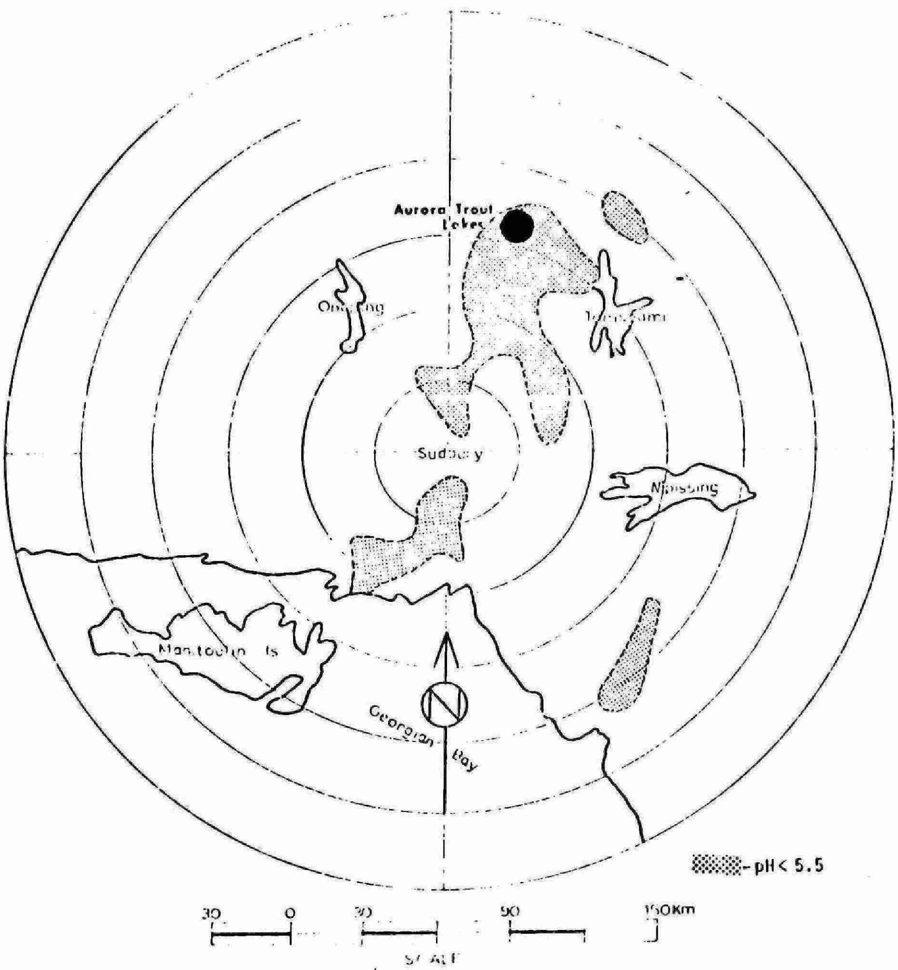
The study lakes are located in the Townships of Donovan, Brewster, Corley and Gamble, within the Temagami Provincial Forest. The area exhibits the rough topography typical of the Precambrian shield with terrain composed predominantly of Precambrian gneiss bedrock, exposed or covered by a thin veneer of soils. Forest cover consists primarily of mature pine and spruce.

With the exception of Jerry Lake, which drains south to the Lady Evelyn River system, the study lakes are part of an interconnected watershed flowing to Smoothwater Lake and thence north via the east branch of the Montreal River. Figure 2 is a map of the study area showing the locations of the study lakes and flow patterns within the watershed. As shown in Figure 2, Whitepine Lake receives drainage from Little Whitepine, Whirligig, Aurora and Little Aurora lakes and in turn flows to Marina Lake which also collects drainage from Sunnywater Lake (via Wilderness Lake). Smoothwater Lake receives the combined drainage from the watershed by inflow from Marina Lake.

Table 1 summarizes morphometric data for the study lakes. As shown in Table 1, the lakes show considerable morphological variation with surface area ranging from 4.1 to 912.5 ha and

FIGURE 1

DISTRIBUTION OF LOW pH LAKES (<5.5) IN THE GREATER SUDBURY AREA, AFTER CONROY ET AL, 1978, SHOWING THE LOCATION OF THE STUDY LAKES.



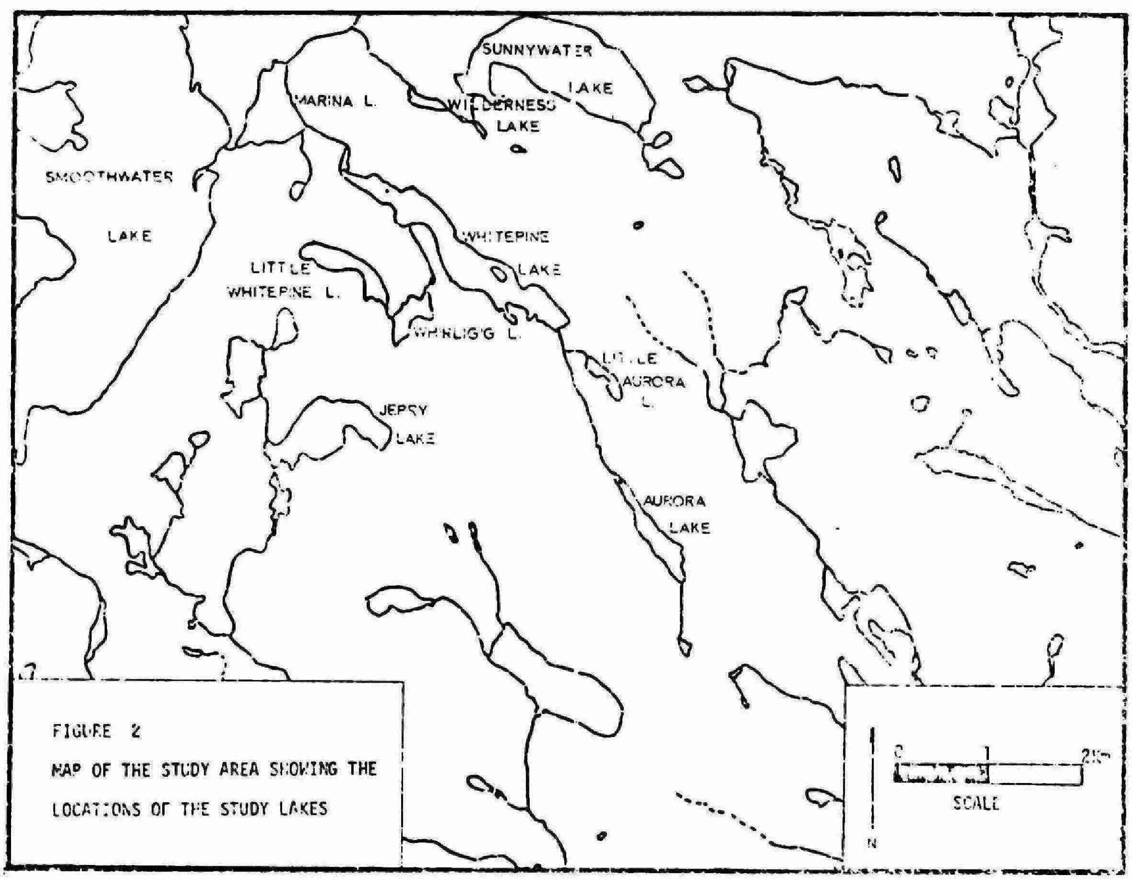


FIGURE 2

MAP OF THE STUDY AREA SHOWING THE LOCATIONS OF THE STUDY LAKES

mean depth varying between 0.8 and 32.1 m. The parent lakes of the aurora trout, Whitepine, Whirligig and Wilderness, have areas of 77.8, 11.4 and 4.1 ha and mean depths of 7.0, 4.7 and 5.7 m respectively.

TABLE 1

MORPHOLOGICAL CHARACTERISTICS OF THE STUDY LAKES

LAKE	SURFACE AREA (A_0) ha	MAXIMUM DEPTH m	MEAN DEPTH($\bar{z}$) m	VOLUME($A_0 \times \bar{z}$) m^3
Aurora	19.2	15.2	5.2	1.0×10^6
Jerry	56.7	27.4	11.8	6.7×10^6
Little Aurora	5.5	1.8	0.8	4.4×10^4
Little Whitepine	21.7	12.2	5.7	1.2×10^6
Marina	37.0	16.8	4.6	1.7×10^6
Smoothwater	912.5	88.4	32.1	2.9×10^8
Sunnywater	141.8	90.2	24.1	3.4×10^7
Whitepine	77.8	21.3	7.0	5.4×10^6
Whirligig	11.4	9.1	4.7	5.4×10^5
Wilderness	4.1	9.1	5.7	2.3×10^5

METHODS

Data collection on the study lakes was carried out according to two different formats.

Smoothwater, Jerry, Sunnywater and Whitepine lakes were sampled by float equipped aircraft as part of the Extensive Monitoring Programme of the Sudbury Environmental Study. A summary of the sampling methodology employed is provided in Conroy et al, 1978. The analyses performed are listed in Table 2 (modified from Conroy et al, 1978).

The remaining study lakes were visited by canoe and/or foot since their relatively small size precluded the use of aircraft.

In the lakes sampled by canoe (Little Whitepine, Whirligig, Aurora, Marina and Whitepine [1]) temperature and dissolved oxygen depth profiles were taken with a YSI model 54 dissolved oxygen - temperature meter and duplicate 1000 ml water samples were collected in sterile glass bottles from one m above bottom and one m below surface. Surface samples were obtained by lowering the sample bottles in a weighted container, to a depth of one m. Bottom samples were collected with a Van Dorn sampler. One bottle of each duplicate set was acidified with two mls of concentrated HNO_3 for subsequent metals analyses while the companion sample was left unpreserved for major ion and nutrient analyses. An aliquot of each unpreserved sample was used for in situ measurement of pH (Radiometer model 29 meter) and conductivity (Electronic Switchgear model MC-1 meter).

[1] Whitepine Lake was sampled twice by aircraft and twice by canoe.

TABLE 2

PARAMETERS INVESTIGATED, EXTENSIVE MONITORING PROGRAMME, SUDBURY ENVIRONMENTAL STUDY

FIELD ANALYSES

In situ	Field Laboratory
Secchi disc	pH
dissolved oxygen	conductivity
temperature	alkalinity
	calcium
	magnesium
	sulphate

LABORATORY ANALYSES (M.O.E. LABORATORY - TORONTO)

sodium	chlorophyll *a*
potassium	zinc
silica	copper
chloride	nickel
carbon	lead
nitrogen	cadmium
phosphorus	iron

NOTE 1: all analyses except chlorophyll *a* (euphotic zone composite) performed on both surface (1m) and bottom (1m above bottom) samples.

NOTE 2: for analytical methods see M.O.E., 1975.

Chemical and metals analyses were carried out at the M.O.E. laboratory in Toronto. Additionally, at each depth, a 175 ml "Prince of Wales" bottle was filled to overflowing to exclude air, cooled, and retained for alkalinity titration at the field laboratory in Sudbury.

Phytoplankton samples were collected as euphotic zone composites with a weighted sampler. In most of the lakes, the euphotic zone extended to the lake bottom, therefore samples were collected by lowering a 1000 ml glass bottle with a restricted inlet to one m above bottom and retrieving it at such a rate that the bottle just filled upon reaching surface. In cases where the euphotic zone did not extend to bottom, composite samples were taken to the approximate lower limit of effective light penetration (twice the Secchi disc transparency). Immediately after collection, samples were preserved with $\approx$ 10 mls of Lugols iodine solution. The identification and enumeration of phytoplankton were performed by the M.O.E. Plant Taxonomy Unit, Toronto.

Wilderness Lake was visited solely by hiking; therefore, surface samples only were collected for phytoplankton examination and chemical analyses. Temperature and dissolved oxygen data were not collected on Wilderness Lake.

Little Aurora Lake was reached by canoe; however, due to its shallow depth ($<$ 3m), only surface sample collections and dissolved oxygen and temperature measurements were carried out. For both Little Aurora and Wilderness lakes, sample treatment was identical to that described above.

RESULTS

WATER CHEMISTRY

The results of lake-water analyses for selected chemical constituents are listed in Table 3. The data provided in Table 3 typify the study lakes as dilute, oligotrophic, soft-water systems. Conductivity in all the lakes was very low (35 to 49 µmho/cm) and concentrations of the major ions were correspondingly low. Table 4 summarizes the range in concentration of selected parameters in the study lakes and provides similar data for other Northeastern Ontario lakes (Conroy et al, 1978). Comparison of the data from the present study with that of Conroy et al, indicate that in terms of ionic strength, the study lakes approach the lower limits to be expected in Northeastern Ontario waters. Major ions were present in the proportions Ca > Mg > Na > K for cations and SO_4 > HCO_3 > Cl > NO_3 for anions on a meq/l basis. Generally, the abundance of major ions was similar in all lakes, as shown by an electroneutrality balance of the data (Table 5).

Alkalinity in the study lakes was very low (0 to 2 mg/l as $CaCO_3$), a reflection of the low concentrations of solutes present. Correspondingly, pH was low in all lakes (4.5 to 5.8), considerably below the value considered "typical" of natural Precambrian shield waters (≈ 6.8). Most of the lakes (Jerry, Little Aurora, Sunnywater, Whitepine, Whirligig, Wilderness) exhibited mean surface water pH's in the range 4.5 to 5.0; two lakes (Little Whitepine, Marina) showed pH's between 5.0 and 5.5; while only one lake (Smoothwater) had a mean surface pH exceeding 5.5. Within individual lakes, temporal and depth-related variation in pH was noted; however,

TABLE 3

RESULTS OF SELECTED CHEMICAL ANALYSES

LAKE	NO.	DATE	DEPTH (m)	pH	CONDUCTIVITY (umho/cm)	mg/l ALKALINITY as $CaCO_3$	CALCIUM	MAGNESIUM	SODIUM	POTASSIUM	SULPHATE	SILICA as SiO_2	CHLORIDE	TOTAL CARBON	INORGANIC CARBON	µg/l TOTAL KJELDAHL	FREE AMMONIA	NITRITE	NITRATE	TOTAL PHOSPHORUS	SOLUBLE PHOSPHORUS	SECCHI DISC (m)	CHLOROPHYLL a (mg/m^3)
Aurora	1	02/06/76	1	4.6	41	—	3	<1	0.6	0.4	12.5	1.2	0.4	6	0	190	28	<1	<5	9	<1	—	—
		25/08/76	1	4.5	40	—	3	<1	0.7	0.5	11.0	1.0	—	1	0	10	10	<1	<5	1	—	9.5	—
			12	4.4	39	0.0	3	<1	0.8	0.5	9.0	1.2	—	4	1	70	20	<1	<5	8	—		—
Jerry	2	01/06/76	1	5.0	42	2.0	3	1	0.7	0.4	13.5	1.2	0.3	1	0	80	6	1	29	2	<1	7.0	0.6
			21	5.0	41	1.8	4	<1	0.7	0.4	12.5	1.2	0.3	3	<1	160	20	1	39	5	<1		
		28/07/76	1	4.7	43	0.7	3	1	0.6	0.5	13.0	1.1	0.2	—	—	110	12	<1	15	3	1	18.0	—
			18	4.8	41	0.8	2	<1	0.6	0.5	12.5	1.1	0.2	—	—	220	32	<1	10	2	1		
Little Aurora	3	02/06/76	1	4.7	49	—	3	1	0.7	0.4	13.5	1.3	0.4	5	0	170	14	<1	<5	5	<1	—	—
		25/08/76	1	4.6	49	0.6	3	1	1.0	0.4	14.0	1.0	—	4	1	60	8	<1	<5	2	—		—
Little Whitepine	4	01/06/76	1	5.2	34	—	4	<1	0.6	0.4	11.0	0.8	0.2	3	0	210	22	1	<5	7	<1	6.5	—
			11	5.2	33	—	3	<1	0.6	0.4	11.0	0.8	0.2	4	<1	300	10	1	<5	24	<1		
		24/08/76	1	5.0	35	1.2	3	<1	0.6	0.5	9.5	0.7	—	7	1	100	2	<1	<5	4	—	7.5	—
			11	4.7	34	2.0	3	<1	0.7	0.5	11.0	0.6	—	9	2	290	50	<1	<5	21	—		
Marina	5	01/06/76	1	5.0	38	—	2	<1	—	—	12.5	1.4	0.6	4	0	250	32	<1	10	8	<1	—	—
		24/08/76	1	5.3	38	1.8	3	<1	0.8	0.5	12.0	1.3	—	5	1	20	10	<1	<5	2	—	9	—
			11	5.0	37	2.0	3	<1	0.9	0.5	11.5	1.6	—	5	1	30	18	<1	<5	1	—		
Smoothwater	6	01/06/76	1	5.5	39	1.6	4	1	0.5	0.4	12.5	1.6	0.3	2	0	110	12	1	74	1	1	10	0.4
			39	5.5	40	1.8	4	1	0.5	0.4	12.5	1.6	0.4	2	0	170	14	1	79	5	<1		
		28/07/76	1	5.8	39	1.4	3	1	0.6	0.4	12.5	1.7	0.2	—	—	140	10	<1	10	7	1	12	—
			32	5.5	39	1.5	3	1	0.6	0.4	12.0	1.7	0.2	—	—	220	8	1	54	9	1		
		09/09/76	1	6.1	39	3.0	4	1	0.7	0.4	11.5	1.6	0.3	4	2	160	21	1	69	3	1	14	0.4
			34	5.1	39	2.6	3	1	0.6	0.4	11.0	1.6	0.3	5	2	110	11	1	64	1	1		
Sunnywater	7	01/06/76	1	4.7	38	0.8	—	—	0.5	0.3	10.5	0.6	0.2	<1	0	100	42	1	94	3	<1	15	—
		28/07/76	1	4.6	41	0.2	2	<1	0.4	0.4	10.5	0.7	0.2	—	—	120	14	<1	80	3	<1	15	—
			35	4.6	41	0.2	2	<1	0.4	0.4	10.5	0.7	0.2	—	—	140	18	1	89	2	<1		
Whitepine	8	01/06/76	1	4.7	40	0.4	4	<1	0.6	0.4	12.5	1.4	0.3	3	<1	160	8	1	<5	5	<1	5.0	1.5
			12	4.7	40	0.4	3	1	0.6	0.4	12.0	1.4	0.3	5	0	170	12	1	<5	5	<1		
		28/07/76	1	4.6	40	0.4	2	<1	0.5	0.5	12.0	1.1	0.2	—	—	180	14	<1	5	4	1	10.0	—
			20	4.7	40	0.8	2	<1	0.5	0.5	12.0	1.2	0.2	—	—	160	6	<1	5	2	1		
		26/08/76	1	4.7	39	0.8	3	<1	0.7	0.5	10.0	1.0	—	4	1	80	20	<1	<5	2	—	9.0	—
			11	4.8	39	0.8	3	<1	0.6	0.5	13.0	1.4	—	5	1	20	4	<1	<5	1	—		
		09/09/76	1	5.1	40	1.8	3	<1	0.5	0.5	11.0	0.9	0.3	4	2	160	32	<1	10	2	1	7.0	1.5
			15	5.0	39	2.0	3	<1	0.5	0.5	9.5	1.5	0.4	7	2	290	44	<1	<5	11	1		
Whirligig	9	01/06/76	1	4.8	38	—	3	<1	0.6	0.5	11.0	1.4	0.4	5	0	170	6	1	<5	11	1	4.0	—
			8	4.8	36	—	2	<1	0.6	0.5	11.0	1.5	0.4	8	0	280	64	1	<5	11	1		
		24/08/76	1	4.8	37	0.8	3	<1	0.7	0.5	11.5	0.7	—	8	2	60	12	<1	<5	1	—	5.5	—
			9	5.3	36	2.0	3	<1	0.6	0.5	9.5	1.9	—	10	1	200	18	1	<5	12	—		
Wilderness	10	02/06/76	1	—	38	—	2	1	0.5	0.3	11.0	0.6	0.3	2	0	100	30	<1	85	7	<1	—	—
		26/08/76	1	4.5	38	1.0	2	<1	0.7	0.5	9.0	0.2	—	4	2	250	58	<1	10	7	—	—	—

TABLE 4

COMPARATIVE SUMMARY OF SELECTED CHEMICAL PARAMETERS IN THE STUDY LAKES AND IN OTHER NORTHEASTERN ONTARIO LAKES

PARAMETER	PRESENT STUDY (10 lakes)	CONROY ET AL., 1978 (209 lakes)
pH	4.5 - 5.8	4.3 - 8.4
Conductivity	35 - 49 µmho/cm	24 - 285 µmho/cm
Alkalinity	0.0 - 2.0 mg/l	0.0 - 121.9 mg/l
Calcium	2.0 - 3.7 mg/l	2.0 - 42.0 mg/l
Magnesium	<1 - 1 mg/l	<1 - 14 mg/l
Sodium	0.5 - 0.9 mg/l	0.4 - 11.9 mg/l
Potassium	0.4 - 0.5 mg/l	0.3 - 1.8 mg/l
Sulphate	10.0 - 13.8 mg/l	4.0 - 31.3 mg/l
Silica	0.4 - 1.6 mg/l	0.1 - 3.6 mg/l
Chloride	0.2 - 0.6 mg/l	0.2 - 21.5 mg/l
Total Phosphorus	3 - 7 µg/l	1 - 30 µg/l
Total Nitrogen	107 -223 µg/l	76 - 904 µg/l

NOTE: ranges quoted represent range in mean surface water concentrations for individual lakes

TABLE 5

IONIC BALANCE FOR THE STUDY LAKES

LAKE	Σ CATIONS (Ca^{+2}, Mg^{+2}, K^{+}, Na^{+}, H^{+})	Σ ANIONS (HCO_3^-, Cl^-, SO_4^{-2}, NO_3^-)	DIFFERENCE meq/l	% of total
Aurora	.272 meq/l	.256 meq/l	+.016	3.0
Jerry	.272 meq/l	.310 meq/l	-.038	6.6
Little Aurora	.279 meq/l	.310 meq/l	-.031	5.2
Little Whitepine	.295 meq/l	.243 meq/l	+.052	9.6
Marina	.255 meq/l	.308 meq/l	-.053	9.5
Smoothwater	.303 meq/l	.302 meq/l	+.001	0.2
Sunnywater	.211 meq/l	.236 meq/l	-.025	5.6
Whitepine	.269 meq/l	.262 meq/l	+.008	1.5
Whirligig	.273 meq/l	.262 meq/l	+.011	2.1
Wilderness	.218 meq/l	.237 meq/l	-.019	4.2

NOTE: based on mean surface water concentrations.

no consistent pattern was evident i.e.: both increases and decreases between spring and summer, and with increased depth, were observed. Spring to midsummer variations ranged from 0.1 to 0.6 pH units while differences between surface and bottom water pH were in the range of 0.1 to 1 units.

Consistent with the dilute nature of the study lakes, the abundance of waterborne nutrients was generally low.

Concentrations of total carbon ranged from 1 to 8 mg/l in surface samples, and a tendency toward increasing concentrations with the advancement of summer and in bottom waters was apparent. In all lakes, carbon occurred primarily in the organic form. During spring, inorganic carbon concentrations were consistently below detection limits and during midsummer, although a very slight increase was evident, levels remained low (1 to 2 mg/l)[1].

Total nitrogen (Kjeldahl + nitrite + nitrate) concentrations varied from 107 to 223 µg/l (mean surface values) with from 11 to 59% of the nitrogen occurring in the inorganic form (ammonia + nitrite + nitrate). Generally, ammonia comprised the bulk of the inorganic nitrogen present, however four lakes (Jerry, Smoothwater, Sunnywater, Wilderness) had nitrate levels approaching and in some cases exceeding ammonia concentrations. In the other study lakes nitrate levels were consistently below detection limits (< 5 µg/l). Concentrations of nitrite were uniformly 1 µg/l or less in all lakes.

[1] Recent investigation of the analytical method used for determining inorganic carbon has resulted in a change in that method. The reported values are likely an overestimate.

Significant seasonal and depth related variations in concentrations of total phosphorus were evident. Surface water concentrations in all lakes were generally low (mean values 3 to 7 µg/l) and in most cases a decrease was noted between spring and summer values. Bottom water total phosphorus levels frequently exceeded surface concentrations; however, in most lakes bottom values remained relatively low (< 10 µg/l). Little Whitepine and Whirligig lakes were exceptions exhibiting bottom water total phosphorus concentrations of 21 to 24 and 11 to 12 µg/l respectively. Generally, in all lakes, on all sampling dates, 1 µg/l or less of the total phosphorus present was in soluble form.

Table 6 provides the results of analyses for selected metals. As shown in Table 6, concentrations of lead and cadmium were uniformly low, in all cases at or below the detection limits employed in the analyses (2 and 1 µg/l for lead and cadmium respectively). Nickel and copper levels showed some variation between lakes, depths, and sampling periods; however, generally levels were low - well below the mean values recorded by Conroy et al, 1978 for 209 Northeastern Ontario lakes (14 and 11 µg/l for nickel and copper respectively). It is interesting to note the similarity between the data of Conroy et al, and the reported global mean (10 µg/l) for nickel and copper (Livingstone, 1964). Zinc concentrations, in most cases approached the global (10 µg/l) and Northeastern Ontario (13 µg/l) mean values; however, in six (Aurora, Jerry, Marina, Sunnywater, Whitepine, Whirligig) of the ten lakes studied, anomalously high levels of zinc (22 to 36 µg/l) were detected on at least one sampling date. With the exception of a single surface sample from Sunnywater Lake (36 µg/l) the elevated (> 20 µg/l) zinc concentrations observed were restricted to bottom waters.

TABLE 6

RESULTS OF SELECTED METALS ANALYSES

LAKE	NO.	DATE	DEPTH (m)	µg/l					
				ZINC	COPPER	NICKEL	LEAD	CADMIUM	IRON
Aurora	1	02/06/76	1	12	15	5	<2	<1	110
		25/08/76	1	10	<1	4	2	<1	30
			12	30	<1	4	<2	<1	86
Jerry	2	01/06/76	1	17	7	4	<2	<1	34
			21	14	7	4	<2	<1	53
		28/07/76	1	9	<1	3	<5	<1	13
			18	30	2	10	<2	<1	37
Little Aurora	3	02/06/76	1	13	1	4	<2	<1	42
		25/08/76	1	18	<1	4	<2	<1	25
Little Whitepine	4	01/06/76	1	6	<1	2	<2	<1	64
			11	14	3	2	<2	<1	150
		24/08/76	1	14	3	2	2	<1	14
			11	11	1	<2	<2	<1	160
Marina	5	01/06/76	1	9	1	2	<2	<1	66
		24/08/76	1	8	<1	2	≤2	<1	13
			11	34	<1	2	<2	<1	48
Smoothwater	6	01/06/76	1	8	3	3	<2	<1	14
			39	10	1	2	<2	<1	7
		28/07/76	1	12	<1	2	<2	<1	16
			32	16	2	6	<2	<1	10
		09/09/76	1	8	1	<1	<2	<1	9
			34	6	<1	<1	<2	<1	5
Sunnywater	7	01/06/76	1	36	2	3	2	<1	31
		28/07/76	1	12	2	3	2	<1	35
			35	30	7	2	<2	<1	44
Whitepine	8	01/06/76	1	10	2	2	<2	<1	110
			12	10	6	4	<2	<1	130
		28/07/76	1	10	2	3	<2	<1	45
			20	24	2	2	<2	<1	44
		26/08/76	1	7	<1	2	2	<1	33
			11	8	<1	<2	<2	<1	84
		09/09/76	1	9	1	1	<2	<1	39
			15	6	1	<1	<2	<1	650
Whirligig	9	01/06/76	1	6	<1	2	<2	<1	160
			8	29	4	2	<2	1	380
		24/08/76	1	8	<1	2	<2	<1	110
			9	22	<1	<2	<2	<1	890
Wilderness	10	02/06/76	1	16	1	2	<2	<1	21
		26/08/76	1	10	2	4	2	<1	43

Concentrations of iron showed significant variation with season, depth, and between lakes with concentrations ranging from 5 to 890 µg/l. No definite pattern of variability was evident; however, a strong tendency toward increased iron abundance in bottom waters was observed. The highest concentrations of iron recorded during this study (650 and 890 µg/l) were measured in the bottom waters of Whitepine and Whirligig lakes respectively.

THERMAL AND DISSOLVED OXYGEN CONDITIONS

A summary of temperature and dissolved oxygen measurements performed on the study lakes is provided in Table 7. Figure 3 depicts midsummer temperature and dissolved oxygen depth distributions for selected lakes.

During spring (June 1 and 2), surface water temperatures in the study lakes ranged from 14 to 17°C, indicating considerable post-turnover warming. By midsummer (August 24 to 26) surface temperatures had further increased (17 to 23°C) and thermal stratification was evident in those lakes in which temperature - depth series were taken (see Figure 3).

In Aurora, Little Whitepine, Whitepine, Marina and Whirligig lakes, thermoclines commenced at 11, 9, 8, 6 and 5 m respectively and extended to, or very close to, the lake bottom. Obviously, hypolimnia are virtually absent in these lakes; however, it should be noted that the maximum depths (see Table 1) of Whitepine Lake (21.3 m) and Marina Lake (16.8 m) significantly exceed the depths at the locations sampled during this study (11 m). Significant hypolimnetic

TABLE 7

RESULTS OF TEMPERATURE AND DISSOLVED OXYGEN MEASUREMENTS

ON THE STUDY LAKES 1976

AURORA	02/06/76		25/08/76	
	Temp. (°C)	D.O. (%)	Temp. (°C)	D.O. (%)
1 m	16.7	127	22.0	101
2 m			21.2	101
3 m			21.0	99
4 m			20.8	98
5 m			20.5	98
6 m			20.0	97
7 m			20.0	98
8 m			20.0	97
9 m			19.8	98
10 m			19.0	101
11 m			18.5	122
12 m			15.0	100

JERRY	01/06/76		28/07/76	
	Temp. (°C)	D.O. (%)	Temp. (°C)	D.O. (%)
1 m	14.0	90	21.0	92
18 m				
21 m	6.0	99	13.0	108

LITTLE AURORA	02/06/76		25/08/76	
	Temp. (°C)	D.O. (%)	Temp. (°C)	D.O. (%)
1 m	17.0	85	23.0	107

LITTLE WHITEPINE	01/06/76		24/08/76	
	Temp. (°C)	D.O. (%)	Temp. (°C)	D.O. (%)
1 m	16.0	125	21.5	94
2 m			21.3	94
3 m			21.3	94
4 m			21.0	93
5 m			21.0	93
6 m			20.5	94
7 m			20.3	96
8 m			19.5	95
9 m			18.2	120
10 m			15.9	120
11 m	10.5	111	14.8	98

MARINA	01/06/76		24/08/76	
	Temp. (°C)	D.O. (%)	Temp. (°C)	D.O. (%)
1 m			22.0	103
2 m			22.0	99
3 m			22.0	96
4 m			21.5	95
5 m			21.5	95
6 m			20.0	93
7 m			17.0	120
8 m			13.9	114
9 m			12.5	108
10 m			11.5	87
11 m			10.2	57

SMOOTHWATER	01/06/76		09/09/76	
	Temp. (°C)	D.O. (%)	Temp. (°C)	D.O. (%)
1 m	15.0	102	17.0	85
34 m			7.0	85
39 m	6.0	91		

SUNNYWATER	01/06/76		28/07/76	
	Temp. (°C)	D.O. (%)	Temp. (°C)	D.O. (%)
1 m	15.0	102	21.0	92
35 m			6.0	91

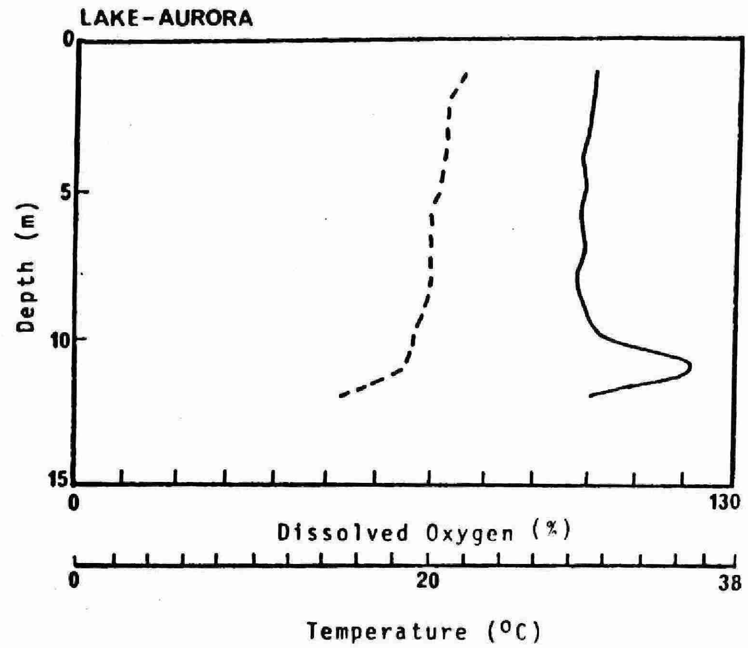
WHITEPINE	01/06/76		26/08/76	
	Temp. (°C)	D.O. (%)	Temp. (°C)	D.O. (%)
1 m	14.0	90	21.7	96
2 m			21.5	98
3 m			21.2	96
4 m			21.0	95
5 m			20.8	96
6 m			20.5	95
7 m			20.0	95
8 m			19.0	100
9 m			16.0	116
10 m	10.0	92	14.1	111
11 m			13.0	106
12 m				

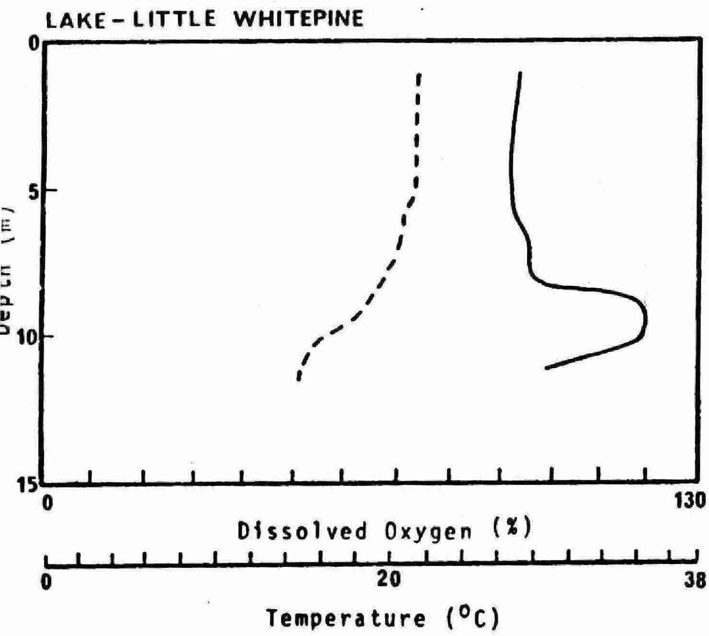
WHIRLIGIG	01/06/76		24/08/76	
	Temp. (°C)	D.O. (%)	Temp. (°C)	D.O. (%)
1 m	16.0	115	22.0	91
2 m			22.0	91
3 m			21.8	91
4 m			21.2	89
5 m			19.2	79
6 m			16.0	76
7 m	7.0	77	11.2	11
8 m			9.0	0
9 m			8.5	0

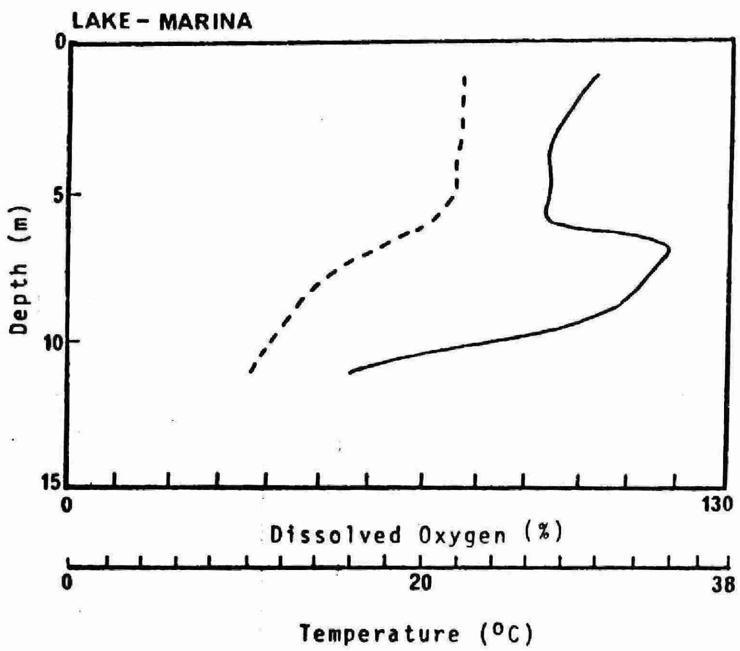
FIGURE 3

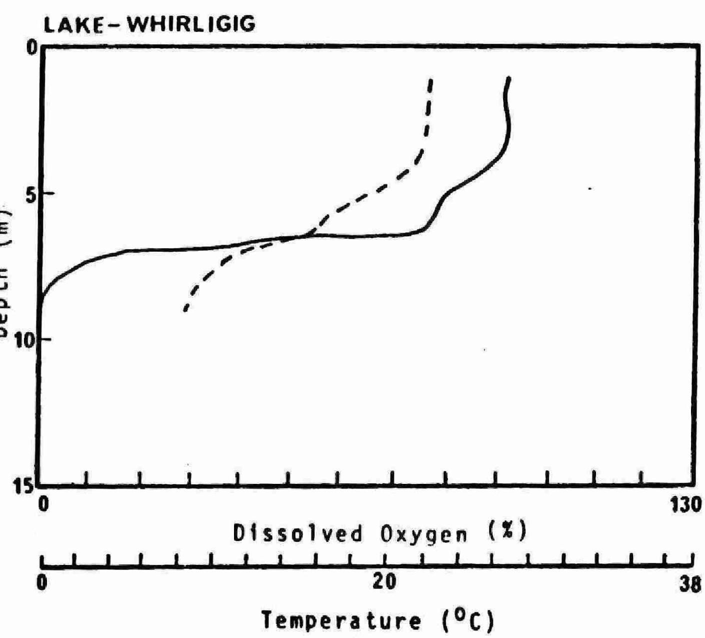
Midsummer Temperature and Dissolved O_2 Depth Distributions For Selected Study Lakes

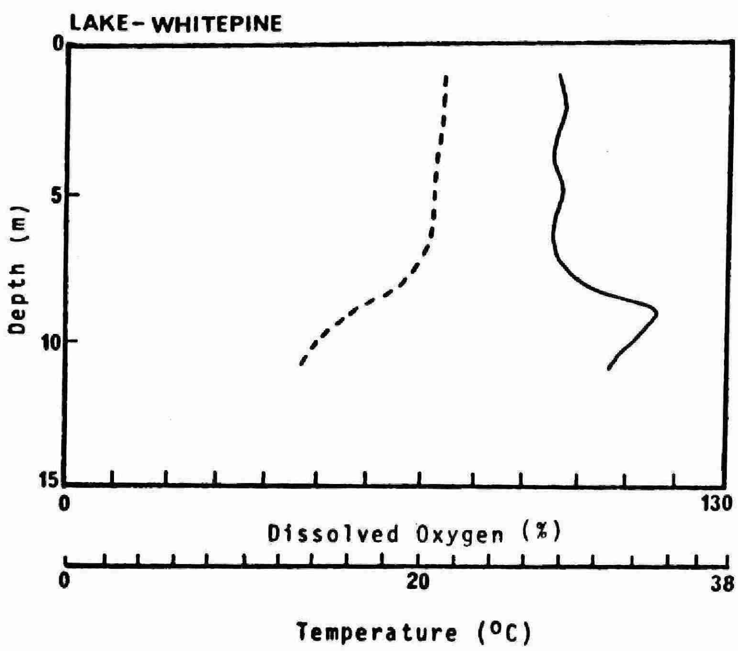
——— Dissolved Oxygen Curve
- - - - - Temperature Curve











volume may exist within the deeper areas of Whitepine and Marina Lakes. The sampling location depths of Aurora, Little Whitepine, and Whirligig lakes more closely approach reported maximum depths.

Although temperature - depth profiles were not taken on Sunnywater, Smoothwater and Jerry lakes, it is likely, due to their comparatively great depth, (see Table 2) that well defined thermal stratification occurs and considerable hypolimnetic volumes are present. Little Aurora Lake would be extremely unlikely to show significant temperature variation with depth since its very shallow nature (< 3m) doubtless permits continuous wind mixing throughout the summer. Wilderness Lake (mean depth 9.1 m) likely exhibits at least some degree of summer stratification with the hypolimnion being minimal or nonexistent.

During the spring (June) sampling, surface water concentrations of dissolved oxygen approached or exceeded saturation in all lakes (range 85 to 127%). Bottom water concentrations were similar to those at surface, with most values slightly above or below saturation (± 15%). With the exception of Whirligig Lake, variation between surface and bottom water oxygen levels was in the order of 10%. Whirligig Lake provided a striking deviation from this pattern with a difference of 38% saturation between surface (115%) and bottom (77%).

During midsummer, surface water dissolved oxygen concentrations continued to approach or slightly exceed saturation; however, significant variation with depth was observed in the five lakes for which depth profiles were obtained (see Figure 3).

Aurora, Little Whitepine and Whitepine lakes showed distinct positive heterograde dissolved oxygen distributions with $\approx$ 20% increases occurring in the region of the thermocline. As indicated previously, thermoclines in these lakes closely approached, or extended to, the lake bottom.

Marina Lake also exhibited a significant pulse of dissolved oxygen in the thermocline; however, the most striking feature of the depth profile was a drastic oxygen reduction in the bottom waters. Dissolved oxygen decreased from 114% saturation at the lower limit of the thermocline to 57% saturation at one m above bottom - a distance of 3m.

Whirligig Lake, the only lake to exhibit a significant bottom water oxygen decline during the late spring sampling, showed a strong clinograde distribution in midsummer. A complete absence of oxygen was recorded in the bottom waters of Whirligig Lake.

Midsummer dissolved oxygen profiles were not completed on the other study lakes; however, spot measurements at surface and bottom indicated no hypolimnial depletion in Jerry, Smoothwater and Sunnywater lakes. In these lakes, all values, surface and bottom, approached or exceeded saturation (85 to 108%). No dissolved oxygen data were obtained for Wilderness Lake.

PHYTOPLANKTON POPULATIONS

The results of the identification and enumeration of phytoplankton from selected lakes are provided in Table 8.

TABLE 8

RESULTS OF THE IDENTIFICATION AND ENUMERATION OF PHYTOPLANKTON

FOR SELECTED STUDY LAKES ('P' denotes presence)

TAXA	Aurora Lake		Little Aurora Lake		Little Whitepine Lake		Marina Lake
	01/06/76	25/08/76	02/06/76	25/08/76	01/06/76	24/08/76	- 25/08/76
CYANOPHYCEAE							
Aphanothece	-	P	-	-	-	-	-
Chroococcus	-	-	-	-	-	-	5
Gomphosphaeria	-	-	-	-	-	-	P
Merismopedia	-	-	-	P	-	-	P
Oscillatoria	-	-	-	1	-	3	-
DINOPHYCEAE							
Gymnodinium	4	585	1	2	-	431	152
Unident. Dinophyceae	162	-	13	28	150	324	169
CHRYSOPHYCEAE							
Bitrichia	P	-	1	-	-	1	1
Chrysochromulina	-	-	-	-	-	-	-
Chrysolykos	-	-	-	-	-	-	-
Chrysophyte (Unident.)	-	-	-	-	-	-	-
Dinobryon	158	7	90	30	2	-	15
Kephyrion	-	-	P	-	1	P	P
Mallomonas	6	-	165	970	-	-	-
Synura	-	-	3	-	-	-	-
Uroglenopsis	1	-	-	-	-	-	-
Unident. Chrysomonad	33	11	5	5	28	35	41
Unident. Cyst	2	-	-	-	-	-	-
CRYPTOPHYCEAE							
Chryptomonas	184	-	17	9	14	31	19
Katablepharis	P	-	-	-	-	-	-
Rhodomonas	P	-	-	-	-	-	-
Unident. Cryptophyceae	-	-	-	-	-	1	-
EUGLENOPHYCEAE							
Trachelomonas	-	-	-	-	-	-	-
CHLOROPHYCEAE							
Botryococcus	-	-	-	-	-	-	-
Chlamydomonas	4	-	-	P	5	3	6
Closterium	-	-	-	-	-	-	-
Dictyosphaerium	-	-	-	-	-	-	-
Gloeocystis	-	-	P	-	-	-	1
Kirchneriella	-	-	P	-	-	-	-
Koliella	-	-	-	-	2	15	1
Monoraphidium	-	-	-	-	-	P	P
Mougeotia	-	-	59	-	-	-	-
Netrium	-	-	-	-	-	-	-
Oocystis	-	-	-	-	-	2	-
Scenedesmus	-	-	-	-	-	-	-
Scourfieldia	-	-	-	-	-	P	-
Tetraedron	-	-	-	P	-	3	-
Unident. Desmid.	5	-	-	-	17	-	2
Unident. Chlorophyceae	-	-	-	1	-	3	-
BACILLARIOPHYCEAE							
Achnanthes	-	-	-	-	-	-	-
Asterionella	-	-	-	-	36	-	-
Eunotia	-	-	-	-	-	-	-
Nitzschia	-	-	-	-	-	-	-
Synedra	-	-	-	-	2	-	-
TOTAL μ^3/ml	557×10^3	603×10^3	354×10^3	1046×10^3	257×10^3	852×10^3	412×10^3

TABLE 8 - continued

TAXA	Whirligig Lake 01/06/76	Whirligig Lake 24/08/76	Whitepine Lake 02/06/76	Whitepine Lake 26/08/76	Wilderness Lake 02/06/76	Wilderness Lake 26/08/76
CYANOPHYCEAE						
Aphanothece	-	-	P	-	-	-
Chroococcus	-	-	-	-	-	-
Gomphosphaeria	-	-	-	-	-	-
Merismopedia	-	P	-	-	1	-
Oscillatoria	8	6	-	-	-	-
DINOPHYCEAE						
Gymnodinium	10	287	9	2	63	17
Unident. Dinophyceae	278	858	116	58	-	14
CHRYSOPHYCEAE						
Bitrichia	-	1	-	-	-	-
Chrysochromulina	P	-	-	-	-	-
Chrysolykos	-	-	P	-	-	-
Chrysophyte (Unident.)	1	-	-	-	-	-
Dinobryon	-	9	7	1	-	1
Kephyrion	-	P	P	-	-	-
Mallomonas	-	-	-	35	-	36
Synura	-	-	-	-	-	-
Uroglenopsis	-	-	-	-	-	-
Unident. Chrysomonad	128	86	20	29	8	32
Unident. Cyst	-	-	3	-	4	-
CRYPTOPHYCEAE						
Chryptomonas	63	21	31	-	-	-
Katablepharis	-	-	-	-	-	-
Rhodomonas	-	-	P	-	-	P
Unident. Cryptophyceae	-	-	-	-	-	-
EUGLENOPHYCEAE						
Trachelomonas	1	-	-	-	-	-
CHLOROPHYCEAE						
Botryococcus	-	-	-	-	-	41
Chlamydomonas	16	1	20	4	15	1
Closterium	-	-	-	-	62	-
Dictyosphaerium	-	-	-	2	-	3
Gloeocystis	-	-	-	-	-	-
Kirchneriella	-	-	-	-	-	22
Koliella	-	-	4	1	-	-
Monoraphidium	2	12	-	P	-	P
Mougeotia	-	-	-	-	-	-
Netrium	-	-	-	-	7	-
Oocystis	-	-	-	-	-	P
Scenedesmus	-	-	-	-	-	1
Scourfieldia	-	-	-	-	-	-
Tetraedron	-	-	-	-	-	-
Unident. Desmid.	13	39	12	-	-	-
Unident. Chlorophyceae	-	27	1	-	-	-
BACILLARIOPHYCEAE						
Achnanthes	-	-	-	-	47	-
Asterionella	-	-	-	-	-	-
Eunotia	-	-	-	-	2	-
Nitzschia	-	-	-	-	-	P
Synedra	-	-	-	-	-	-
TOTAL μ^3/ml	520×10^3	1347×10^3	223×10^3	132×10^3	209×10^3	168×10^3

Pictorial representations of the abundance and composition of phytoplankton communities are given in Figure 4. The areas of the circles in Figure 4 are proportional to cell volume per ml.

Aurora Lake exhibited similar phytoplankton biomass on both sampling dates (557 and 603 x 10^3 μ^3/ml during June and August respectively); however, a significant change in community composition occurred. During June, Chrysophyceae, Dinophyceae and Cryptophyceae were co-dominant comprising approximately 30% each of the total biomass and a small representation of Chlorophyceae was evident. During August composition had shifted to complete dominance by Dinophyceae with a small occurrence of Chrysophyceae.

Little Aurora Lake showed a significant increase in phytoplankton biomass between June and August (354 to 1046 x 10^3 μ^3/ml); however, community composition remained relatively similar with strong dominance (75 to 96%) by Chrysophyceae on both occasions and lesser occurrence of Dinophyceae, Cryptophyceae, and Chlorophyceae. During June, Cyanophyceae were not collected from Little Aurora Lake; however, in August, a small occurrence (1 x 10^3 μ^3/ml) was noted.

In Little Whitepine Lake an increase in the phytoplankton biomass from 257 to 852 x 10^3 μ^3/ml occurred between June and August. Community composition remained similar; however, certain changes are noteworthy. During June, Dinophyceae dominated (58%) and subdominant populations of Bacillariophyceae, Chlorophyceae, Cryptophyceae and Chrysophyceae were present. By August, dominance by Dinophyceae had increased (89%), Baccillariophyceae had disappeared, and a small population of Cyanophyceae had developed. The occurrence

Figure 4: Abundance and Composition of Phytoplankton Populations in Selected Study Lakes

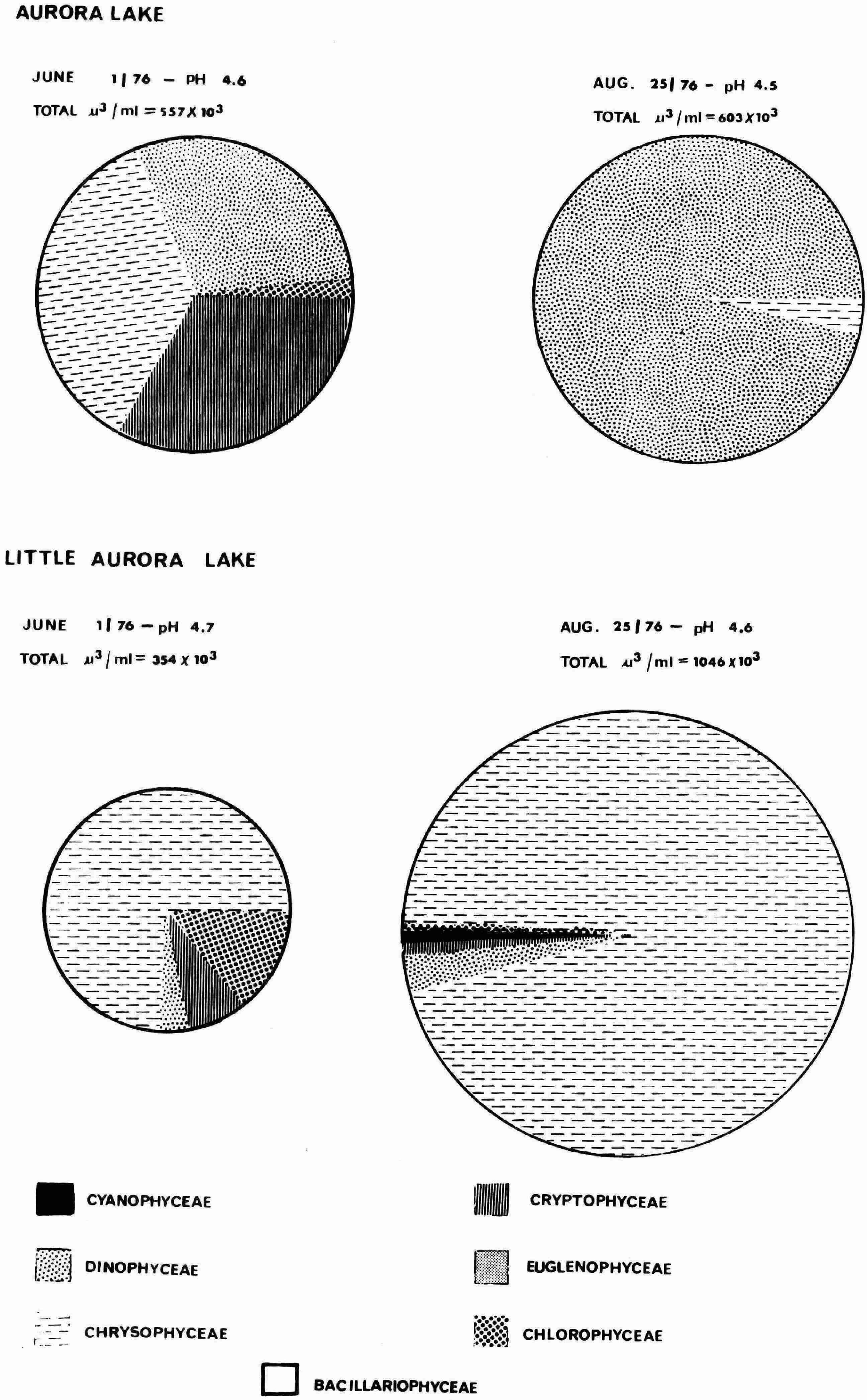
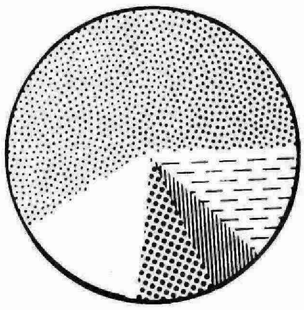


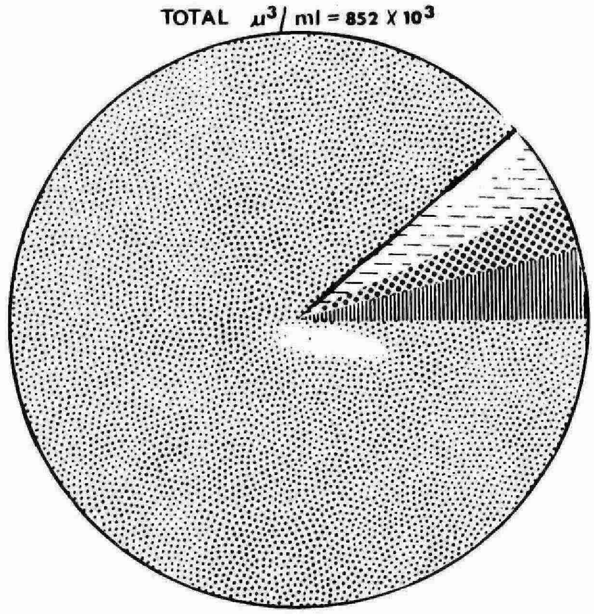
Figure 4: Cont.

LITTLE WHITEPINE LAKE

JUNE 1/76 – pH 5.2
TOTAL $\mu^3/ml = 257 \times 10^3$

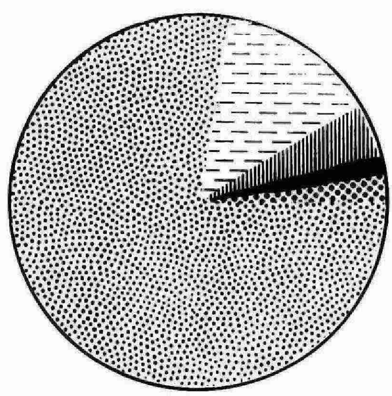


AUG. 24/76 – pH 5.0
TOTAL $\mu^3/ml = 852 \times 10^3$



MARINA LAKE

AUG. 25/76 – pH 5.3
TOTAL $\mu^3/ml = 412 \times 10^3$



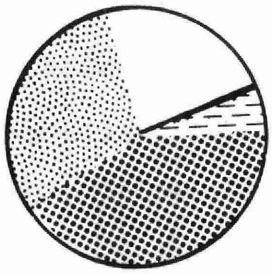
CYANOPHYCEAE
DINOPHYCEAE
CHRYSOPHYCEAE
CRYPTOPHYCEAE
EUGLENOPHYCEAE
CHLOROPHYCEAE
BACILLARIOPHYCEAE

Figure 4: Cont.

WILDERNESS LAKE

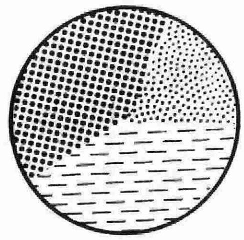
JUNE 2 / 76 – pH – n/a

TOTAL μ^3/ml = 209 X 10^3



AUG. 26 / 76 – pH 4.5

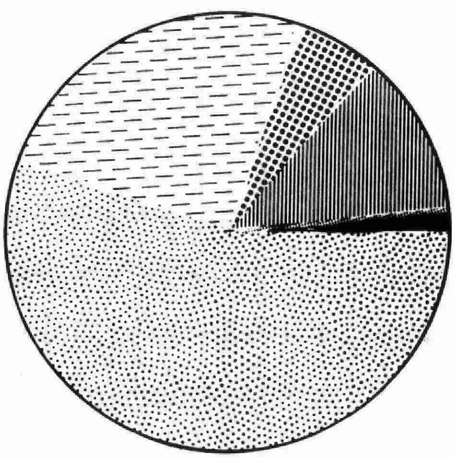
TOTAL μ^3/ml = 168 X 10^3



WHIRLIGIG LAKE

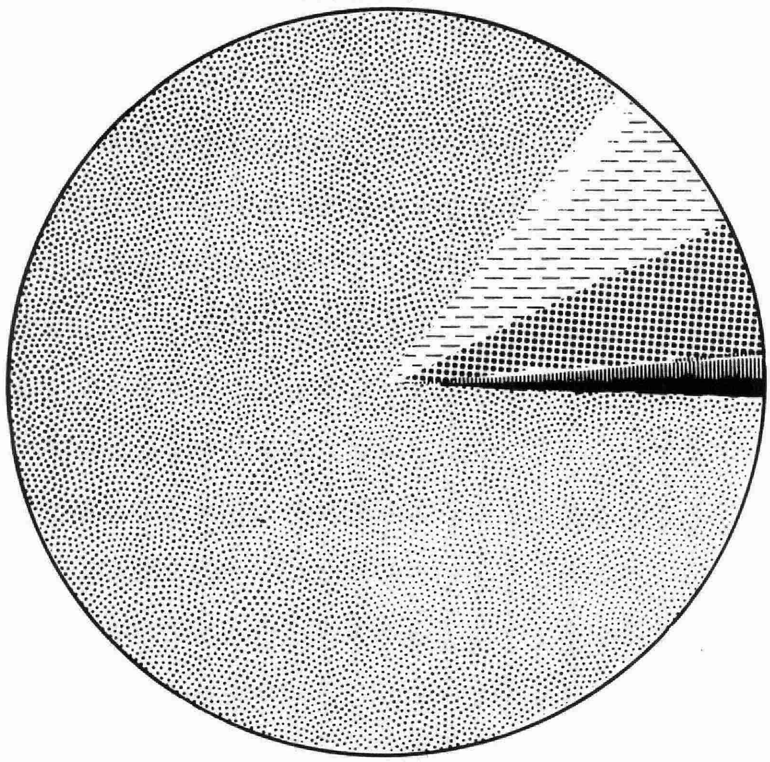
JUNE 1 / 76 – pH 4.8

TOTAL μ^3/ml = 520 X 10^3



AUG. 24 / 76 – pH 4.8

TOTAL μ^3/ml = 1347 X 10^3



CYANOPHYCEAE

CRYPTOPHYCEAE

DINOPHYCEAE

EUGLENOPHYCEAE

CHRYSOPHYCEAE

CHLOROPHYCEAE

BACILLARIOPHYCEAE

Figure 4: Cont.

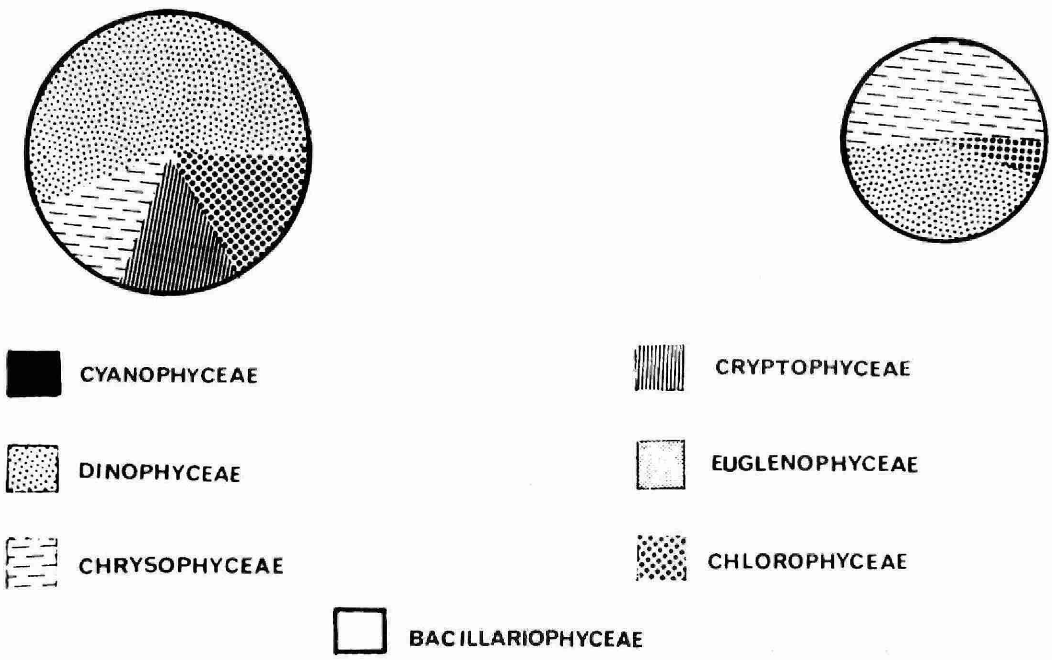
WHITEPINE LAKE

JUNE 2 / 76 – pH 4.7

TOTAL $\mu^3/ml = 223 \times 10^3$

AUG. 26 / 76 – pH 4.7

TOTAL $\mu^3/ml = 132 \times 10^3$



of populations of Chlorophyceae, Cryptophyceae and Chrysophyceae continued in August.

Phytoplankton were not sampled in Marina Lake during June; therefore, no observations on seasonal changes can be made. In August, the structure of phytoplankton populations in Marina Lake was quite similar to midsummer community composition in Little Whitepine Lake, i.e.: dominance by Dinophyceae and representation (in order of decreasing abundance) by Chrysophyceae, Cryptophyceae, Chlorophyceae, and Cyanophyceae. Total phytoplankton biomass was, however, considerably lower in Marina Lake (412 x 10^3 μ^3/ml).

Wilderness Lake exhibited low phytoplankton biomass during both June and August (209 and 168 x 10^3 μ^3/ml respectively). In June, Chlorophyceae dominated (40%) and significant populations of Dinophyceae and Bacillariophyceae occurred. Chrysophyceae were present (12 x 10^3 μ^3/ml) and a small population of Cyanophyceae (1 x 10^3 μ^3/ml) was noted. In August, Chlorophyceae and Chrysophyceae were co-dominant ($\approx$40% each) and the remainder of the population was comprised of Dinophyceae. Although present in June, Bacillariophyceae and Cyanophyceae were not collected during the August sampling.

The phytoplankton community of Whirligig Lake, in June, was dominated by Dinophyceae (55%) and a significant proportion (25%) of the total population was composed of Chrysophyceae. Significantly smaller populations of Chlorophyceae and Cryptophyceae were present and the occurrence of Cyanophyceae and Euglenophyceae was noted. In August, dominance by Dinophyceae increased (85%) and lesser representation by Chrysophyceae, Chlorophyceae, Cryptophyceae, and Cyanophyceae

continued. No representatives of Euglenophyceae were found. Biomass increased from 520 to 1347 x 10^3 μ^3/ml between June and August.

Whitepine Lake demonstrated a slight decline in phytoplankton populations between June and August (223 to 132 x 10^3 μ^3/ml). In June, Dinophyceae were dominant (56% of total) with Chrysophyceae, Cryptophyceae, and Chlorophyceae comprising approximately equal proportions of the remainder of the community. In August, Cryptophyceae had disappeared and Dinophyceae and Chrysophyceae were co-dominant with a small representation of Chlorophyceae in evidence.

General examination of the phytoplankton results indicates that of the six lakes for which both June and August data were collected, three lakes (Little Aurora, Little Whitepine and Whirligig) showed significant increases in phytoplankton biomass between spring and summer; two lakes (Whitepine and Wilderness) exhibited slight population decreases; and one lake (Aurora) showed minimal variation.

Representatives of Dinophyceae were generally strongly dominant in the study lakes, particularly in midsummer when they comprised from 78 to 97% of the total phytoplankton populations in four of the seven lakes sampled. Of the remaining three lakes, two contained co-dominant populations of Dinophyceae. In many cases Dinophyceae were not identified to Genus; however, the frequent abundance of <u>Gymnodinium</u> was noted.

Although not generally reaching dominant status, (only dominant in Little Aurora Lake) Chrysophyceae were consistently an important constituent of phytoplankton communities - occurring in all lakes on all sampling dates. Dinobryon and Mallamonas were often abundant; however, in many cases unidentified genera comprised the majority of the Chrysophyceae present. Of considerable taxonomic significance is the discovery, in Little Aurora Lake, of two species of the genus Pseudokephyrion (Chrysophyceae), new to science (Nicholls, 1977).

Representatives of Cryptophyceae and Chlorophyceae were also present in most lakes and in some cases contributed a significant proportion of the phytoplankton biomass. The occurrence of Crytophyceae was restricted almost solely to the genus Cryptomonas. The presence of other genera was documented; however, numbers were insufficient to permit quantification. Numerous representatives of Chlorophyceae were recorded with Chlamydomonas and Monoraphidium being the most frequently occurring genera.

Cyanophyceae occurred in four of the seven lakes sampled; however, in all cases populations were very low ($< 8 \times 10^3$ μ^3/ml). Oscillatoria and Merismopedia were the most common genera.

Bacillariophyceae (diatoms) were found in two lakes, and in both cases only in June. Representatives of the genera Achnanthes and Asterionella were the predominant diatoms in Wilderness and Whitepine lakes respectively.

The occurrence of Euglenophyceae was limited to a very small population (1×10^3 μ^3/ml) of a single genera, Trachelomonas, recorded in Whirligig Lake during June.

DISCUSSION

THE ACIDIFICATION PHENOMENON

The depression of pH in surface waters due to atmospherically conveyed acidic inputs has become a major, international, environmental concern. Research has indicated (Oden, 1967; Likens, 1976), widespread elevation in the acidity of precipitation, directly reflecting emissions of contaminants, notably sulphur species, from anthropogenic sources. Man's activity, particularly fossil fuel combustion and mineral smelting, contributes large quantities of sulphur dioxide to the atmosphere, where through oxidation and reaction with water vapour, sulphuric acid (H_2SO_4) is formed. Although sulphur oxides generally appear to be the major cause of the acid rain phenomenon, oxides of nitrogen may be significant contributors in some cases. The resultant "Acid Rain" has caused large scale lake and river acidification in many areas of the world, including Sweden (Dickson, 1975), Norway (Gjessing et al, 1976), Canada (Beamish and Harvey, 1972), and the U.S.A. (Schofield, 1976). In addition, acid precipitation is often associated with elevated concentrations of metals, and in areas of significant atmospheric inputs, the combined effects of elevated metal levels and low pH are of major concern due to potential additive and/or synergistic effects.

The effects of acid precipitation on aquatic systems are most pronounced in regions of highly resistant geology. The low contribution of solutes (including major buffer forming species) to waters from such terrain (Conroy and Keller, 1976), results in minimal acid neutralization capacity and

correspondingly even relatively minor additions of strong mineral acids may have a profound effect on pH. In areas of more weathering, calcareous terrain, buffer forming species are more abundant and waters may absorb considerable acidic inputs without exhibiting pH reductions (Kramer, 1976a).

The low pH of the study lakes is evidence of a serious, ecological problem - the phenomenon of lake and river acidification. Dilute, oligotrophic Precambrian Shield lakes typically react slightly acid; however, the pH of the study lakes (4.5 to 5.8) is much lower than the usual pH of such waters ($\approx$6.8). In terms of H^+ activity, this represents a difference of one to two orders of magnitude.

Kramer, (1976b), in a study of precipitation chemistry in Ontario documented generalized low precipitation pH (mean - 4.7) based on data from an extensive network of bulk collectors (rain and dry fallout). Kramer's data for a location close to the present study area (Florence Lake, $\approx$ 20 km southeast) indicated a mean pH value of 4.2, lower than the overall mean for his study and one and one-half orders of magnitude more concentrated in H^+ than predicted by the reaction of CO_2 and water vapour, the natural controlling mechanism (pure H_2O + average abundance of atmospheric CO_2 $\rightarrow$ pH = 5.65, Hem, 1970).

As indicated previously (Figure 1) the present study area falls within a zone of depressed surface water pH associated with atmospherically conveyed acidic inputs. Excessive precipitation acidity coupled with inherently low buffering capacity appears to have resulted in the severe pH depression observed in the study lakes and in numerous other waters in the greater Sudbury area.

In an attempt to trace the acidification process in the study lakes, historical pH data (primarily from Ministry of Natural Resources lake surveys) were obtained where available, and compared to data from the present study. Figure 5 is a plot of historical and recent pH measurements in the study lakes versus year of sampling. Note from Figure 5 that a linear regression for all data indicates a pH decline of 0.09 units per year, comparable to observations on other lakes in the greater Sudbury area (0.16 units/year - Beamish and Harvey, 1972; 0.09 units/year - Conroy et al, 1978); and in Scandinavia (0.03 to 0.05 units/year - Gjessing et al, 1976). It should also be noted however, that the historical measurements are very limited in number and their reliability may be somewhat questionable. Further, due to buffering effects, a linear pH decline would not be expected in the natural aquatic system. The pattern of lake acidification would likely more closely follow that of a H_2SO_4/lakewater titration, as shown in Figure 6. If a line of best fit is applied to the data points in Figure 5, some resemblance (i.e. rapid pH depression (H^+ elevation) when buffering capacity is exhausted) to the shape of a H_2SO_4 titration curve is evident, likely providing a more realistic depiction of the acidification process in the study lakes.

Figure 5 indicates the apparent general pattern of pH decline in the lakes of the study area; however, it is important to note that the rate, and degree of acidification shows variation between lakes - directly reflecting variations in local lithology, lake morphometry, residence times, and acidic loadings. Based on the very limited data available for individual study lakes, mean annual pH declines ranged from 0.04 to 0.14 units and correspondingly present surface water

FIGURE 5

PLOT OF THE APPARENT pH DECLINE IN THE STUDY LAKES BASED ON RECENT AND HISTORICAL MEASUREMENTS

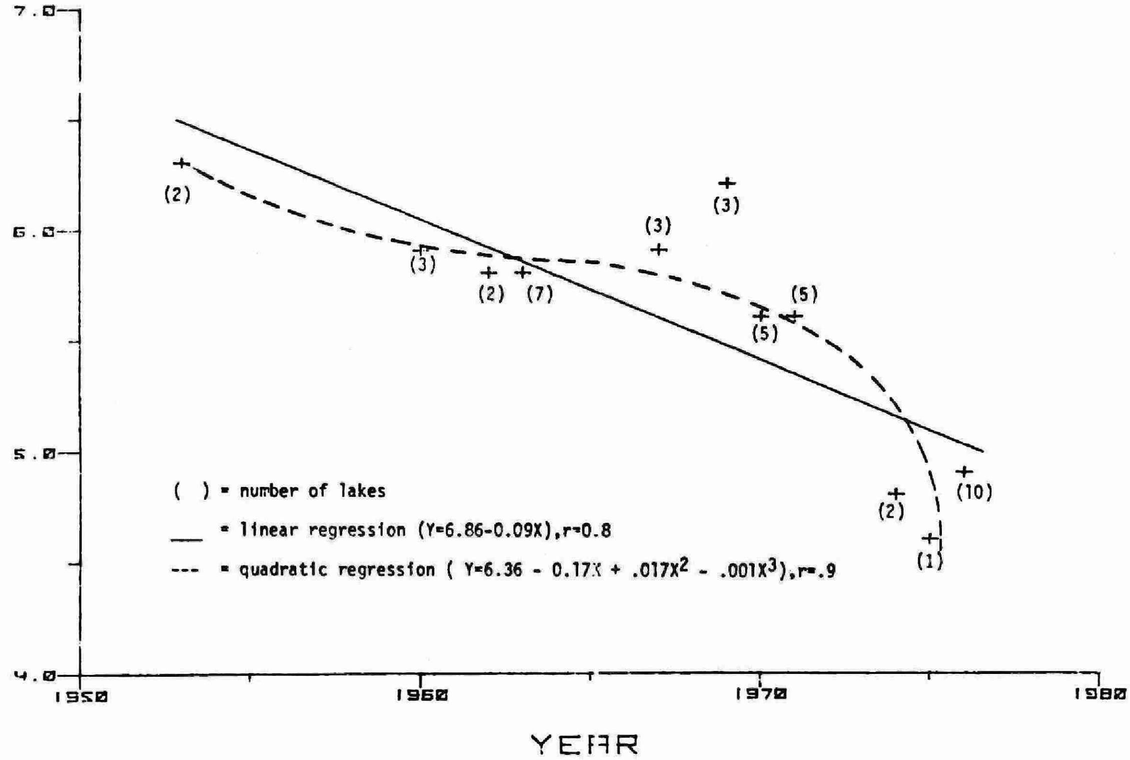
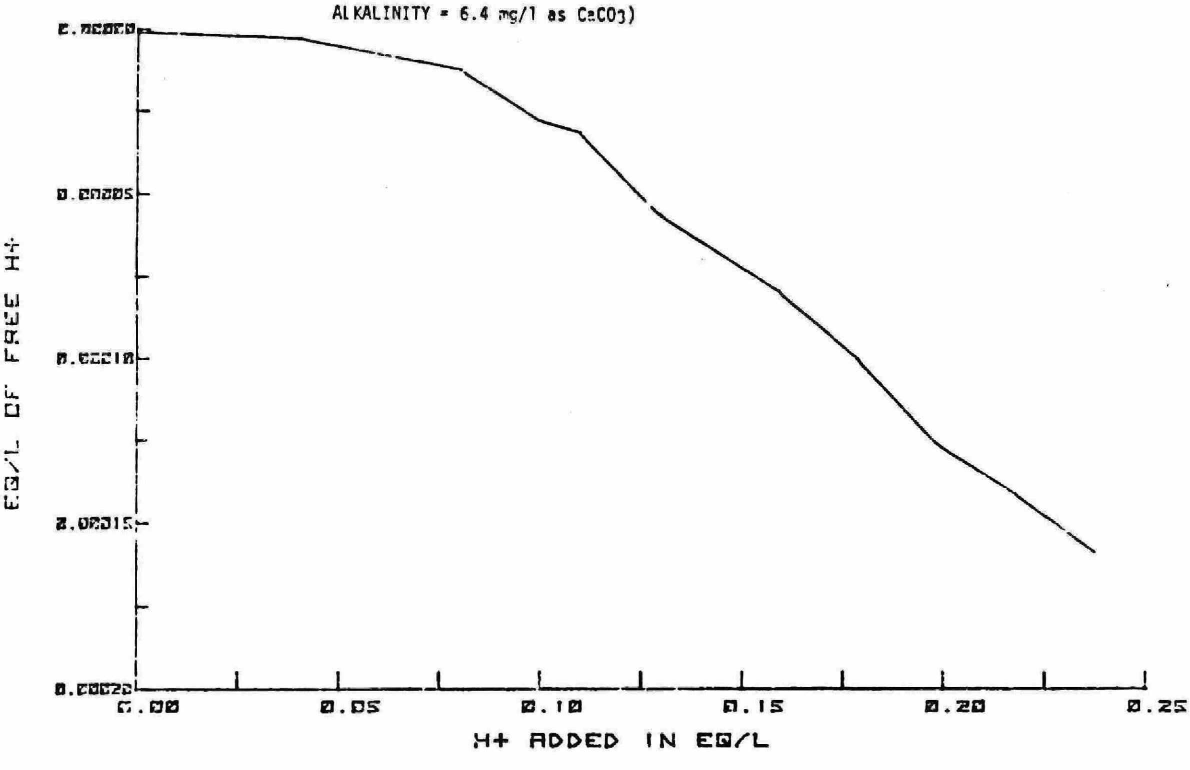


FIGURE 6

PLOT OF TYPICAL H_2SO_4 LAKEWATER TITRATION CURVE (TITRATION DATA FOR MILLERD LAKE (LAFRANCE, 1978), pH = 6.5, CONDUCTIVITY = 67umhos/cm ALKALINITY = 6.4 mg/l as $CaCO_3$)



pH varies significantly between lakes. Although most lakes exhibited very low pH (4.5 to 5.0), Smoothwater, the downstream lake in the watershed had a mean pH of 5.8.

In the consideration of acidification rates, it is also important to note natural seasonal pH fluctuations, which may mask long term trends. In this study, spring to midsummer pH variation in surface waters (0.1 to 0.6 units) greatly exceeded yearly declines as indicated by comparison of recent and historical data (0.04 to 0.14 units).

As mentioned previously, acid precipitation often contains elevated concentrations of heavy metals. Based on data from the present study, however, significant deposition of metals does not appear to be occurring in the study lakes. Waterborne concentrations of metals were generally relatively low, with the exception of occasional, anomalously high bottom water concentrations of zinc and iron which are likely attributable to geologic or lake metabolic rather than atmospheric controls.

BIOLOGICAL RESPONSES TO ACIDIFICATION

Fish

Damage to fish populations provides the most dramatic example of adverse biological effects due to acidification. Severe depression and/or elimination of fish populations due to atmospherically induced acidification has been documented in Scandinavia (Jensen and Snekvik, 1972) and in the U.S.A. (Schofield, 1976).

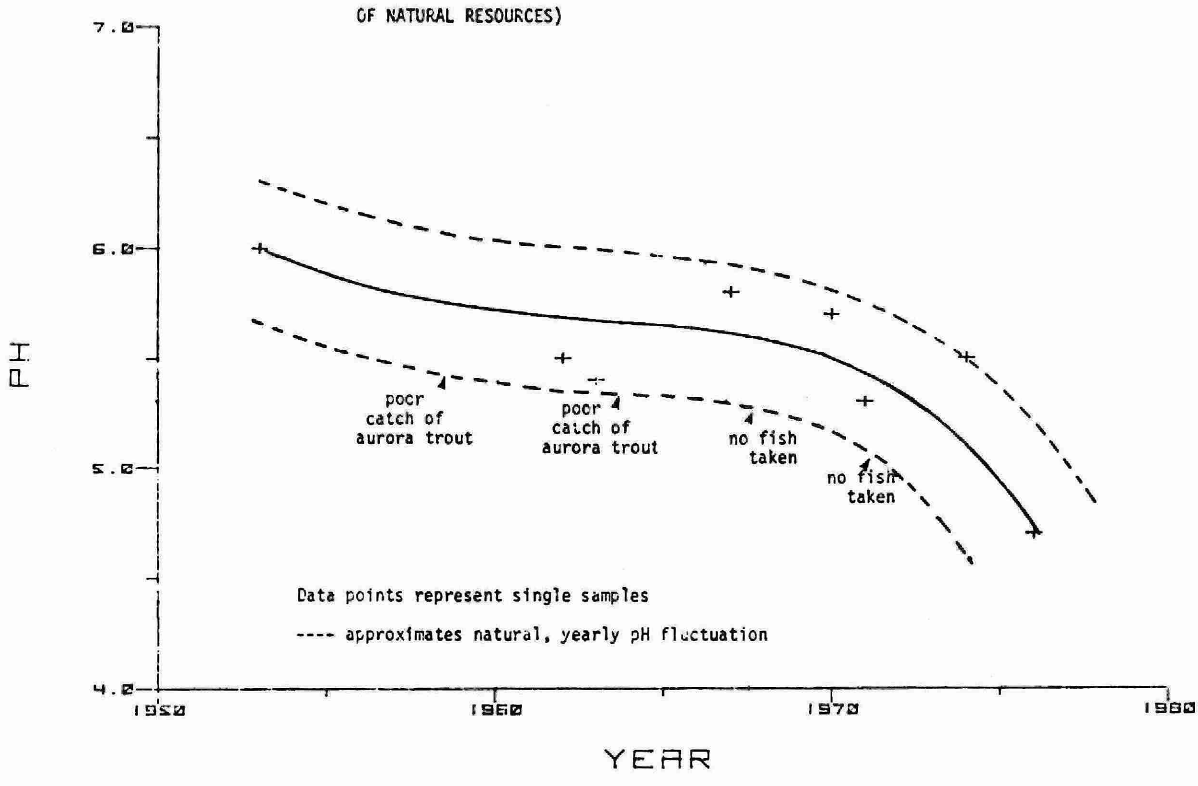
In Ontario, Beamish (1974), described significant pH depression and resultant fish mortality in lakes of the Killarney area, near Sudbury, and attributed the problem to acidic inputs from the atmosphere. Further study in the greater Sudbury area, (Conroy et al, 1978), showed the existence of a large (5300 km^2) zone of lakes with depressed pH (< 5.5) extending northeast and southwest from the smelting centre. Lakes within this zone, which encompasses the present study area, were remarkable for the number of lakes exhibiting depressed or extinct salmonid (brook trout - Salvelinus fontinalis, lake trout - Salvelinus namaycush) fisheries. In 37 of the 139 lakes with records of indigenous salmonid populations sampled within the greater Sudbury area populations were extinct and in an additional 33 lakes populations were poor.

Generally, based on the literature (see Conroy et al, 1978) it appears that at pH below 5.5 reproductive success of salmonids is impaired and below pH 5.0 salmonids are generally eliminated. Figure 7 depicts the apparent pH decline in Whitepine Lake, the largest of the aurora trout parent lakes, and includes historical observations on fishery status obtained from the Ontario Ministry of Natural Resources. As shown in Figure 7 the data exhibit considerable scatter; however, the general pH decline follows the pattern indicated in Figure 5 for all pH data from the study lakes. Note that the earliest recorded pH for Whitepine Lake (6.0 - 1953) is somewhat lower than expected naturally, possibly reflecting an early stage in the acidification process. If an arbitrary confidence width of $\pm$ 0.3 pH units, representative of natural fluctuation, is applied to the plot it appears that minimum surface water pH (indicative of the maximum potential biological effect) reached the level potentially injurious to salmonid

populations (5.5) in the late 1950's. This observation agrees well with lake survey results on Whitepine Lake which showed a very low catch of aurora trout per netting effort during 1958. Subsequent netting during 1962-63 showed the continuing presence of aurora trout but in low numbers. By 1967, aurora trout had apparently disappeared from Whitepine Lake - none were captured during a significant netting effort. It is important to note (see Figure 7) that by the late 1960's minimum pH likely approached 5.0, the value at which salmonid communities are typically eliminated, providing good agreement with the observed absence of aurora trout during the 1967 netting.

FIGURE 7

PLOT OF APPARENT pH DECLINE IN WHITEPINE LAKE, WITH OBSERVATIONS ON FISHERY STATUS INCLUDED. (HISTORICAL INFORMATION FROM MINISTRY OF NATURAL RESOURCES)



The disappearance of aurora trout populations in Whirligig and Wilderness lakes appears to follow the pattern outlined for Whitepine Lake. Fisheries data were not obtained for Wilderness Lake, however Whirligig Lake yielded small catches of aurora trout during 1960 and 1963 while none were captured during 1967.

The other study lakes did not have indigenous aurora trout, but all supported natural populations of brook and/or lake trout and in two lakes (Smoothwater and Marina) also walleye (*Stizostedion vitreum*).

Smoothwater and Marina lakes exhibited viable populations of lake trout and walleye, and lake trout, brook trout, and walleye respectively during the most recent netting (1969). Based on pH data from the present study, Smoothwater Lake (pH 5.8) likely continues to support a self-sustaining fishery; however, at the apparent rate of pH decline (0.14 units/year) fishery problems may occur during the 1980's. The low pH recorded in Marina Lake during the present study (5.2) suggests potentially problematic water quality from a fisheries viewpoint; however, it is interesting to note that an accessory measurement taken during 1977 indicated a pH of 6.5, suitable for fish survival. Additional sampling is required to investigate this discrepancy.

The remaining study lakes, Sunnywater, Little Whitepine, Little Aurora, Jerry and Aurora, appear to have lost their salmonid populations, a direct reflection of depressed pH (4.5 to 5.1). Netting surveys between 1960 and 1967 captured no salmonids in Aurora, Sunnywater, Little Aurora or Little Whitepine lakes. Jerry Lake contained brook trout during the most recent netting 1962-63; however, the present pH

(4.9) suggests that continuing populations of salmonids are unlikely.

Phytoplankton

The elimination of fish populations provides perhaps the most obvious expression of adverse biological effects due to lake acidification; however, other less apparent influences extend to all trophic levels in aquatic systems showing induced acidification, including zoobenthos (Conroy et al, 1976), zooplankton (Sprules, 1975), and phytoplankton (Conroy et al, 1976).

Effects at the primary trophic level, phytoplankton, are particularly significant, since through the food chain, such effects are translated to all succeeding trophic levels in the aquatic system.

It has been suggested (Kwiatkowski and Roff, 1976), that acidification causes significant reduction in primary productivity and phytoplankton biomass; however, other evidence (Dillon et al, 1977) indicates that the generally low productivity of acidified lakes relative to non-acidified lakes may be primarily a reflection of naturally lower nutrient availability. Since acidified lakes generally occur in areas of highly resistant terrain, their nutrient supply, and therefore productivity are expected to be very low. Lakes with sufficient buffering capacity to neutralize acidic inputs (i.e.: non-acidified lakes) are typically located in areas of more weathering terrain where lithospheric contributions of solutes including buffering species and nutrients are more abundant and correspondingly biological activity in the aquatic system is higher.

Table 9 summarizes pH, total phosphorus concentrations, and phytoplankton biomass[1] in selected study lakes and provides comparison with data for other acidified and non-acidified lakes with comparable phosphorus concentrations (summarized from Dillon et al, 1977). From Table 9 it appears that phytoplankton biomass in the study lakes is similar to that of other acidified Ontario lakes which in turn exhibit biomass comparable to that of circumneutral lakes with similar nutrient concentrations.

TABLE 9

TOTAL PHOSPHORUS, pH, AND PHYTOPLANKTON BIOMASS IN ACIDIFIED AND NON ACIDIFIED LAKES LAKES WITH LOW PHOSPHORUS CONCENTRATIONS (SUMMARIZED FROM DILLON ET AL, 1977) WITH DATA FOR SELECTED STUDY LAKES INCLUDED.

pH	Total P µg/l	Phytoplankton Biomass mg/l	Source
4.2 - 5.1	3 - 12	0.26 - 0.73	5 lakes (various authors - see Dillon et al, 1977)
5.6 - 7.8	5 - 15	0.1 - 0.83	10 lakes (various authors - see Dillon et al, 1977)
4.5 - 5.1[1]	3 - 14[2]	0.18 - 0.93	7 lakes (present study).

Note 1: mean surface water values
Note 2: mean values considering all depths

1 Phytoplankton data from present study were converted from μ^3/ml to mg/l assuming an algal density of one.

Although phytoplankton biomass in the study lakes does not appear to be depressed due to the low pH, significant alteration in the community composition of phytoplankton populations is evident, as has been previously observed in acidic lakes (Dillon et al, 1977).

Dilute, circumneutral, Precambrian Shield lakes are typically dominated by populations of Chrysophyceae or Chrysophyceae and Bacillariophyceae (Schindler and Holmgren, 1971) and in some cases by Cyanophyceae (Conroy et al, 1976).

In acidic lakes, the majority of the standing stock is comprised of Chlorophyceae, Dinophyceae and Cryptophyceae, with Chrysophyceae also of significance (Scheider et al, 1976). Generally Bacillariophyceae and Cyanophyceae occur rarely at low pH (Scheider et al, 1976, Kramer, 1976c); however, in some studies dominant populations of Cyanophyceae have been documented in acidic lakes (Conroy et al, 1976, Kwiatkowski and Roff, 1976). Johnson et al, 1970, in a study of adjacent acidified and non-acidified lakes reported that many species of Bacillariophyceae, Chrysophyceae and Cyanophyceae which developed in the unaffected lake were absent or very scarce in the affected lake. It should be noted that direct, intensive comparison of data from the above studies is difficult due to differences in reporting units.

Phytoplankton populations in the present study lakes closely follow the general pattern of community composition in acidic lakes as outlined above, i.e. predominance of Chlorophyceae, Dinophyceae, Crytophyceae and Crysophyceae with

generally rare occurrences of Bacillariophyceae and Cyanophyceae. Dinophyceae (never continuously dominant in dilute, nutrient poor, circumneutral lakes -Yan et al, 1977) were generally strongly dominant in the acidic study lakes and Chrysophyceae were consistently an important group, reaching dominance in one lake. Cryptophyceae and Chlorophyceae were consistently present and in some cases formed a significant proportion of the standing stock although not reaching dominant status.

Cyanophyceae were present in four of the seven lakes sampled however in all cases populations were very low. Bacillariophyceae occurred only in two lakes, in relatively low numbers.

ADDITIONAL LIMNOLOGICAL OBSERVATIONS

In general, the study lakes appear to be dilute, unproductive, oligotrophic Precambrian Shield lakes as indicated by low concentrations of solutes (conductivity 35 to 49 μmho/cm), high Secchi disc transparency (4 to 18 m) and low to moderate phytoplankton populations (132 x 10^3 to 1347 x 10^3 μ^3/ml). Consistent with their oligotrophic status, the lakes exhibited generally low nutrient concentrations (means of 3 to 7 ug/l, 15 to 116 μg/l, and 0 to 1 mg/l for surface water total phosphorus, inorganic nitrogen, and inorganic carbon respectively) and in most lakes, dissolved oxygen remained abundant (approaching or exceeding saturation) throughout the water column with little depletion evident in bottom waters. The positive heterograde dissolved oxygen distributions observed in the smaller study lakes are typical of small, well protected, oligotrophic shield lakes.

Whirligig Lake deviated from the above pattern, showing a clinograde dissolved oxygen depth profile with a complete lack of oxygen in the bottom waters. It is noteworthy that Whirligig Lake also exhibited the highest surface water total phosphorus concentration (11 $\mu g/l$), the highest population of phytoplankton (1347 x 10^3 μ^3/ml) and the lowest Secchi disc transparency (4 m) recorded during the study. The anaerobic conditions in the bottom waters of Whirligig Lake during midsummer, possibly resulting from incomplete spring turnover, apparently induce recycling of materials from the lake sediments as reflected by elevated bottom water concentrations of iron (890 $\mu g/l$) and phosphorus (12 $\mu g/l$). Phosphorus recycled by this mechanism may increase the waterborne supply available to the primary trophic level (algae) in Whirligig Lake and contribute to the apparently more productive water quality conditions observed in this lake relative to the other study lakes.

Marina Lake was the only other study lake to exhibit a significant dissolved oxygen reduction with depth; however, the minimum recorded concentration (6 mg/l) remained sufficient for the survival of cold-water fish species including salmonids.

It has been indicated (Grahn et al, 1974) that in some Scandinavian acidified lakes depressed pH has resulted in retarded nutrient recycling from lake sediments. The impairment of nutrient recycling appears attributable, in part, to a shift from bacterial to less efficient fungal decomposition under acidic conditions.

During the present study, detailed observation revealed no fungal mats in any of the lakes and as indicated, phytoplankton biomass appeared similar to non-acidified lakes of similar phosphorus concentrations. Unfortunately, no reliable historical data are available to indicate whether or not any reduction in the waterborne nutrient supply has occurred, with acidification, in the study lakes.

In the consideration of nutrient, phytoplankton and dissolved oxygen relationships in the study lakes certain additional observations merit mention.

Ministry of Natural Resources lake surveys between 1960 and 1967 documented heavy accumulations of algae on nets set overnight in Aurora, Whitepine and Whirligig lakes. During the present study, an attempt was made to sample periphyton in Whitepine Lake by suspending a plexiglass plate 5 m below the lake surface and allowing 3 months for colonization. At the end of the exposure period, underwater inspection, by snorkelling, revealed the presence of a significant accumulations of periphytic algae on the artificial substrate. Unfortunately, the extremely fragile nature of the attached material resulted in loss during retrieval, precluding identification. Visual underwater examination of several areas of the lake bottom, near shore, indicated a bottom covering of a loose floc (greatly disturbed by a diver's passage) of largely undecomposed algae, similar in appearance to that observed on the plexiglass substrate. Further visual observations during 1976 also showed the presence of large beds of an unidentified filamentous form of Chlorophyceae in many shallow bays of the lake.

Subsequent investigation during the summer of 1977, revealed a similar growth of Chlorophyceae, identified at that time as *Mougeotia*, in Little Aurora Lake, where it formed large mats at the outflow and in shoreline areas (Nicholls, 1978). *Mougeotia* has been identified as an important component of the benthic community in acidic Swedish lakes (Grahn et al, 1974).

REFERENCES CITED

Beamish, R. J. and H. H. Harvey, 1972. Acidification of the La Cloche Mountain lakes, Ontario, and resulting fish mortalities. J. Fish. Res. Bd. Can., 29: 1131-1143.

______________ 1974. Loss of fish populations from unexploited remote lakes in Ontario, Canada, as a consequence of atmospheric fallout of acid. Wat. Res., 8:85 - 95.

Conroy, N.I. and W. Keller, 1972. Report on a preliminary survey of selected lakes in the southwest portion of Swastika Forest District. Internal report, Ontario Ministry of the Environment.

___________, K. Hawley, W. Keller and C. Lafrance, 1976. Influences of the atmosphere on lakes in the Sudbury area. Proc. First Spec. Symp. on atmospheric contribution to the chemistry of lake waters. J. Int. Assoc. Great Lakes Res., 2: 146 - 165.

__________ and W. Keller, 1976. Geological factors affecting biological activity in precambrian shield lakes. Can. Mineral., 14: 62 - 72.

__________, K. Hawley, and W. Keller, 1978. Extensive monitoring of lakes in the Greater Sudbury Area, 1974-76. Ontario Ministry of the Environment.

Dickson, W., 1975. The acidification of Swedish lakes. Institute of Freshwater Research, Drottningholm, Rept. No. 54: 8 - 20.

Dillon, P.J., N.D. Yan, W.A. Scheider and N.I. Conroy, 1977. Acidic lakes in Ontario: Characterization, extent, and responses to base and nutrient additions. Ontario Ministry of the Environment Report.

Gjessing, E.T., A. Henricksen, M. Johannessen and R. Wright, 1976. Effects of acid precipitation on freshwater chemistry. In - impact of acid precipitation on forest and freshwater ecosystems in Norway. SSNF Research Report, 6/76: 65 - 85.

Grahn, O.H., H. Hultberg and L. Landner, 1974. Oligotrophication - a self accelerating process in lakes subjected to excessive supply of acid substances. Ambio 3: 93 - 94.

Hem, J. D., 1970. Study and interpretation of the chemical characteristics of natural water. U. S. Geol. Survey Water Supply Paper 1473.

Henn, A. W. and W. H. Rinkenbach, 1925. Description of the aurora trout (Salvelinus timagamiensis), a new species from Ontario. Ann. Carnegie Museum, 16: 131 - 141. (not seen).

Jensen, R. W. and E. Snekvik, 1972. Low pH levels wipe out salmon and trout populations in southernmost Norway. Amio 1: 223 - 224.

Johnson, M.G., M.F.P. Michalski and A.E. Christie, 1970. Effects of acid mine wastes on phytoplankton communities of two northern Ontario lakes. J. Fish. Res. Bd. Can. 27: 425 - 444.

Kramer, J. R., 1976 a. Geochemical and lithological factors in acid precipitation. Proc. First. Int. Symp. on acid precip. and the forest ecosystem. USDA. Tech. Rept. NE 23: 611 - 617.

____________ 1976 b. Fate of atmospheric sulphur dioxide and related substances as indicated by chemistry of precipitation. Dept. of Geology, McMaster University. Hamilton, Ontario.

____________ 1976 c. Assessment of the ecological effects of long-term atmospheric material deposition. Dept. of Geology, McMaster University. Hamilton, Ontario.

Kwiatkowski, R. E. and J. C. Roff, 1976. Effects of acidity on the phytoplankton and primary productivity of selected northern Ontario lakes. Can. J. Bot. 54: 2546 - 2561.

Lafrance, C., 1978. Personal Communication.

Likens, G. E., 1976. Acid Precipitation. Special Report, Chem. and Eng: 29 - 44.

Livingstone, D. A., 1964. Data of Geochemistry. Chemical composition of rivers and lakes. U.S. Geol. Survey Professional Paper 440-G.

McKay, H. H., 1964. Fishes of Ontario. Ontario Dept. of Lands and Forests.

M.O.E. (Ministry of the Environment - Ontario), 1975. Outlines of analytical methods.

Nicholls, K. H., 1977. Two new species of Pseudokephyrion (Chrysophyceae) in the plankton of a lake. J. Phycol. 13: 410 - 413.

____________, 1978. Personal Communication.

Oden, S., 1967. The acidification of air and precipitation its consequences on the natural environment. Seminar, Ecological Research Committee, Swedish Nat. Sci. Res. Council, Sveagen 166, Stockholm 23.

O.W.R.C., (Ontario Water Resources Commission), 1970. Preliminary report on the influence of industrial activity on lakes in the Sudbury area (1969 - 70).

Sale, P.F., 1967. A re-examination of the taxonomic position of the aurora trout. Can. J. Zool. 45: 215 - 225.

Scheider, W. A., B. Cave, and J. Jones, 1976. Reclamation of acidified lakes near Sudbury, Ontario by neutralization and fertilization. Ontario Ministry of the Environment report.

Schindler, D.W. and S. K. Holmgren, 1971. Primary production and phytoplankton in the Experimental Lakes Area, northwestern Ontario, and other low carbonate waters, and a liquid scintillation method for determining 14C activity in photosynthesis. J. Fish. Res. Bd. Can. 28: 189 - 201.

Schofield, C. L., 1976. Effects of acid precipitation on fish. Int. Conf. on the effects of acid precipitation, Telemark, Norway.

Sprules, G. W., 1975. Midsummer crustacean zooplankton communities in acid stressed lakes. J. Fish. Res. Bd. Can., 32: 389 - 395.

Yan, N.D., W. A. Scheider and P. J. Dillon, 1977. Chemical and biological changes in Nelson Lake, Ontario following experimental elevation of lake pH. Proc. Wat. Poll. Res. Can. 12: 213 - 231.

ACKNOWLEDGEMENTS

This report is provided as a contribution to the Sudbury Environmental Study from the Northeastern Region.

The author, W. Keller, acknowledges the assistance of the following persons or agencies during the study.

N. Conroy and K. Hawley participated in the field investigations and sample collections. Further thanks are due to N. Conroy, for technical review of the manuscript.

K. H. Nicholls offered constructive comments on the manuscript and provided additional information on the study lakes based on personal observations.

N. D. Yan provided critical review of the report.

Members of the Sudbury Environmental Study Technical and Steering Committees provided technical and editorial review of the report.

L. Mortsch and N. Vincent assisted in the compilation of data and preparation of figures.

S. Legault typed and corrected the manuscript.

The Temagami District Office of the Ministry of Natural Resources provided accessory information, including morphometric and fisheries data, on the study lakes.